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Office of Naval Research
Code 321 OT
800 North Quincy Street
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Ref. Grant No. N00014-90J-4063

Dear Tom:

Attached herewith is the Final Report of the refernced grant. If you need further information, do not hesitate to contact me. We sincerely appreciated ONR's support of our work.

Sincerely,

Don L. Boyer

cc: H.J.S. Fernando

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Final Report
Experimental and Theoretical Studies of Wakes in Stratified Flows
Grant No. N00014-90J-4063

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Goal

The long range goal of this research was to obtain, by laboratory experimentation and associated theoretical/numerical analysis, an increased understanding of the dynamics of stratified flow past blunt obstacles including two-dimensional ones such as right circular cylinders and three-dimensional ones such as spheres. Emphasis was given to such phenomena as blocking, flow separation, vortex shedding, lee-wave generation, unsteady characteristics of the free stream, and lift and drag on the obstacles in question.

Approach

The experiments employed a computer-controlled tow tank, 12.2 m long, 30.5 cm deep and 40.6 cm wide; time-dependent speeds in the range $0.1 \leq U \leq 15.0$ cms^{-1} were obtainable. The flows were observed by utilizing a variety of flow visualization techniques, including dye tracers, electrolytic precipitation, neutrally buoyant particle tracers and laser-induced fluorescence. A two-component laser-Doppler velocimetry system and hot film anemometer system were used for obtaining quantitative measures of the motion fields. An image processing system for obtaining motion fields from neutrally buoyant particle tracers was also used in the later stages of the project. Concurrent with the laboratory experimental phase of the program, theoretical and numerical analyses of the motion fields were conducted.

Summary of Some of the Principal Results

1. Steady Uniform Flow Past a Sphere

Experiments on linearly stratified flow past a sphere elucidated eight characteristic flow patterns. For each flow type, descriptions and physical interpretations of the flows were given. The findings included: (i) Fully-attached, unseparated flows were not observed down to Re = 6, where Re is the Reynolds number; (ii) For Fi < 0.2, where Fi is the internal Froude number, the flow is constrained to horizontal planes, with strong vertical coherency and vertical wake structure, the horizontal center-plane of which resembles homogeneous flow past long vertical cylinders; (iii) When the internal structure is near its resonance (relative to the size of the sphere), overturning rotors are observed for Fi = 0.2-0.4 (this resonant wave structure was observed to effectively suppress separation from the sphere at the larger values of Fi); (iv) Flows with Fi = 0.4 represent the transition from flows which are dominated by internal wave motions to motions where wave motion, stratification and viscous effects are equally important (kinematic and topological arguments were used to explain this transition process); (v) Further increases in Fi-Re yield wake flows which become increasingly unsteady, first in an ordered symmetric way and subsequently less symmetric and periodic, until the wake flow undergoes a transition to turbulence at Re = 2000; (vi) Owing to vertical collapse, wakes in stratified flows have substantially larger horizontal scales than vertical ones, and the vertical thickness at the onset of collapse can be predicted by invoking a balance between vertical inertia forces and buoyancy forces; (vii) The far wake is shown to develop into a pancake, quasi two-dimensional vortex street whose Strouhal number is approximately the same as that of vortex shedding in the near wake of spheres in homogeneous fluids; and (viii) The onset of turbulence, its initial growth, collapse and fossilization can be successfully explained using scaling arguments.

2. Internal Waves Generated by a Turbulent Wake

Experiments were conducted in the Reynolds number and Froude number ranges $2.0(10)^3 \leq \mathrm{Re} \leq 12.9(10)^3$ and $2.0 \leq Fi \leq 28.0$, respectively. Two distinct flow regimes were observed. For smaller Re, Fi combinations, the turbulent wake grows in a roughly axisymmetric manner to a maximum diameter and then collapses slowly. At larger Re, Fi combinations, the wake is characterized by large-scale spiraling coherent structures.

3. Horizontal Oscillation of a Sphere in a Linearly Stratified Fluid

The flow field induced by a sphere oscillating horizontally in a linearly stratified fluid was studied using a series of laboratory experiments. The resulting flows are shown to depend on the Stokes number β, the Keulegan-Carpenter number KC and the internal Froude number Fi. For Fi < 0.2, it was shown that the nature of the resulting flows is approximately independent of Fi and, based on this observation, a flow regime diagram in the β-KC plane was developed. The flow regimes include: (i) fully-attached flow; (ii) attached vortices; (iii) local vortex shedding; and (iv) standing eddy pair. An internal wave flow regime was also identified, but, for such flows, the motion field is a function of Fi as well. Some quantitative measures were given to allow for future comparisons of the results with analytical and/or the experiments of Tatsuno and Bearman (1990) on right circular cylinders oscillating in homogeneous fluids.

4. Stratified Turbulent Wake Behind a Cylinder

A comprehensive series of experiments was carried out to study the behavior of turbulence in the wake of a cylinder. The evolution of various length scales, turbulent velocities and the rate of dissipation were measured and some interesting characteristics of the stratified turbulence were delineated. Some salient findings were the length-scale relationships, two dimensionalization of the turbulence and the behavior of fossil turbulence. The results were interpreted in the framework of available theoretical ideas and geophysical observations on stratified turbulence.

5. Rotating Oscillatory Flow Past a Cylinder

This experimental program demonstrated the effect of background rotation (vertical) on the flow of a homogeneous incompressible fluid past a vertical cylinder oscillating in a lateral direction. The experiments demonstrated, for example, that a cylinder in pure oscillation induces a mean anticyclonic (clockwise) current around the cylinder for the case of Northern Hemisphere (anticlockwise) rotation. Such observations have been made in oceanic situations concerning the interaction of tidal currents with islands and seamounts.

6. Vortex Shedding of a Horizontally-Translating, Streamwise-Oscillating Sphere

The flow past a horizontally-translating, streamwise-oscillating sphere through a linearly stratified fluid was investigated in a series of laboratory experiments. The pertinent governing parameters were shown to be the internal Froude number Fi, the Reynolds number Re, the Keulegan-Carpenter number KC and the normalized frequency Sf. A KC against Sf regime diagram for flows at Fi = 0.07 and Re = 190 was developed; for these parameters, the flow is approximately two dimensional in the horizontal zone $-1/2 < z/D < 1/2$, where z is the vertical coordinate and D is the sphere diameter. Numerous flow regimes were delineated, and it was shown that the regime boundaries approximate the lines of constant $u_1/u_0 = 2\pi(KC)(Sf)$, where u_1 is the amplitude of the sphere oscillation and u_0 is the magnitude of the mean background flow. Vortex shedding occurs for the entire range of experiments at these Fi, Re values. Lock-on of the shedding frequency to the sphere oscillation frequency occurs for $u_1/u_0 > 0.1$. Flows at large Fi are shown to exhibit three-dimensional motions in the near wake and, owing to stratification, exhibit vertical collapse at a certain distance downstream. The far wake develops into a horizontal vortex street pattern for all flows when stratification is present. At large Fi, Re combinations, turbulent patches are found in the wake. The inverse normalized streamwise distance between shed vortices (an effective Strouhal number) is shown to scale as Sf, independent of KC. Measurements of horizontal separation angles and times for the collapse of the vertical structure were also made.

7. Vertical or Horizontal Oscillation of a Long Right Circular Cylinder

The flow field induced by either the vertical or horizontal oscillation of a long right circular cylinder (axis horizontal) in a linearly stratified fluid was investigated in the laboratory and by a numerical model. Flow regime diagrams in the ω/N against a/D planes for fixed ND^2/ν were developed from the laboratory observations; here ω is the cylinder oscillation frequency, N is the buoyancy frequency, a is the oscillation amplitude and ν is the kinematic viscosity of the fluid. Internal waves were not observed in the far field for experiments for $\omega/N > 1$. On the other hand, for $\omega/N < 1$, the far field is dominated by internal waves. During the early stages of the cylinder oscillation, this wave field is in close accord with linear theory. As time passes, wave reflections from the free surface and the tank boundaries lead to a highly complex flow field. Numerical experiments, under the assumption of incompressible flow and employing the Boussinesq approximation, were carried out for the initial phases of the motion for one case at $\omega/N > 1$ and one at $\omega/N < 1$. The instantaneous streamline, vorticity and density fields obtained from the numerical experiments at various phases in the oscillatory cycle are in good agreement with the laboratory observations.

8. Turbulent Wakes of Stratified Flow Past a Cylinder

Laboratory measurements were carried out to investigate the evolution of a turbulent wake behind a right circular cylinder moving in a linearly stratified fluid. The flow field was determined by the internal Froude number Fi and the Reynolds number Re, but at high Re, Fi becomes the only governing parameter. Measurements show that stratified turbulent wakes can be classified into three flow regimes, based on Fi. When Fi $\lesssim 2$, the wakes do not grow downstream, and remain at approximately constant height. For $2 \lesssim \mathrm{Fi} \lesssim 3$, the wakes grow to a maximum height at $Nt \approx 5$ and then collapse physically; for $Nt \gtrsim 3$, the maximum height is achieved at $Nt \approx 2.5$, before the collapse begins. The evolution of such other length scales as the Ozmidov, Kolmogorov, overturning and Thorpe scales and the maximum Thorpe displacements were measured, and their behavior in the above Fi ranges delineated. Length scale diagrams for the evolution of stratified turbulence in cylinder wakes were constructed, and compared with previous theoretical predictions. The present results provide new insights into the evolution, collapse and two-dimensionalization of stratified turbulent flows.

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